SIGHDT - ATOMIC AND MOLECULAR CROSS SECTIONS FOR HYDROGEN ISOTOPES

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MASTER

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SIGHDT - ATOMIC AND MOLECULAR CROSS SECTIONS FOR HYDROGEN ISOTOPES

Abstract

SIGHDT is a function subroutine for approximating reaction cross sections for hydrogen isotopes. It is available on the OCTOPUS and Controlled Thermo-nuclear Research (CTR) networks at Lawrence Livermore Laboratory.

Introduction

SIGHDT is a function subroutine giving the cross sections for the reactions listed in Table 1. For many CTR applications, it is adequate to approximate the mean reaction rates $\langle\sigma v\rangle$ between a very hot distribution of one particle species with thermal velocity V_E and a cold distribution of another species by

$$\langle\sigma v\rangle = \sigma V_E .$$

This simple reaction rate is available for each reaction listed.

In each case, all available experimental data has been carefully fitted. Extensions beyond the experimental range were done using theoretically plausible formulae and, sometimes, guesswork. This compilation represents the best known data; comments in Table 2 indicate any reservations or lack of data for each cross section.

Curve Fits

A Hewlett-Packard 9100B Calculator^{*}, coupled with its extended memory, plotter, and digitizer, was used to calculate the curve fits. The curves were fitted to N^{th} order polynomials ($N \leq 11$) of the form:

$$y = a_0 + a_1 X + a_2 X^2 + \dots + a_n X^n ; n \leq 11.$$

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Hewlett-Packard provides a calculator program which will do this fit and also give the user a plot of the calculated curve along with the data points. Since X and Y may be any functional form of the data (e.g., $X = X(x) = \ln x$), this program allows one to easily try many different functional forms to obtain the best fit possible. When extrapolating outside experimental ranges, the functions have the asymptotic forms predicted by theory. The complete set of fits is listed as FUNCTION SIGHDT in the Appendix.

Errors

The experimental σ values have a minimum error of 5%. The analytic fit to σ_{exp} is within 1% of the data over the ranges covered by experiment. We were satisfied to discount σ values of less than 10^{-18} cm^2 ; the reactions in which this is done are indicated in the Table 2 comments. The σ values for the different isotopes are calculated at equal velocities to the σ values of the isotope used to generate the data fit.

Use of SIGHDT

SIGHDT is available from photostore on the OCTOPUS network at Lawrence Livermore Laboratory with the following call to ELF

```
ELF RDSALL .273825 : XSECT
```

This will obtain two files: SIGHDT, the LRLTRAN source code of the function, and BSIGHDT, the relocatable - binary file.

On the CTR network, these two files may be obtained from FILEM with:

```
FILEM RDS .773 .XSECT SIGHDT BSIGHDT
```

The source file may be recompiled with your source code, or you may load the relocatable-binary file with your binary file(s).

SIGHDT is called with two arguments, the reaction number (see Table 1) and the incident particle or projectile energy in eV. SIGHDT does not need to know which isotope is the target, as the projectile velocity determines the reaction rate. SIGHDT has multiple entry points which tell the function the

mass of the incident particle and whether to return σ or σV_E . SIGHDT itself is never directly called. Entry points have the following simple mnemonic form. The first three letters of all entries are SIG. These are followed by the projectile name (e.g., SIGH, SIGD, SIGHE, SIGD2, etc.) the function returns σ of the reaction. When the first four letters of any entry are SIGV followed by the projectile name, the function will return σV_E (e.g., SIGVH, SIGVD, etc.). SIGHDT will return σ and $\sigma V_E = 0$ for an incident particle energy of 0 eV. The complete list of projectile names is: E, H, D, T, HE, H2, D2, T2.

Acknowledgments

My thanks to Brendan McNamara, at whose request this routine was written, and to John Hiskes for his help in checking the results of the calculations and in obtaining the original references.

Table 1. Reaction Numbers, reaction and references for SIGHUT. All reactions have the form:

Target (T) + Projectile $\rightarrow$ products

The T on the target side of the reaction is the target species and can be Hydrogen, Deuterium, or Tritium. The T on the projectile side is Tritium.

Reaction No.	Reaction	Reference
1	$T + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\} \rightarrow T^+ + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\} + e^-$ Ionization	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> 363 (1971).
2	$T + e^- \rightarrow T^+ + 2e^-$ Ionization	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> 363 (1971).
3	$T_2 + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\} \rightarrow T_2^+ + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\} + e^-$ Ionization	J. P. Keene, <i>Philos. Mag.</i> <u>40</u> , 369 (1949).
4	$T_2 + e^- \rightarrow T_2^+ + 2e^-$ Ionization	L. J. Keiffer, G. H. Dunn, <i>Rev. Mod. Phys.</i> <u>38</u> 1 (1966).
5	$T_2 + e^- \rightarrow 2T + e^-$ Dissociation	S. J. B. Corrigan, <i>J. Chem. Phys.</i> <u>43</u> , 4381 (1965).
6	$T_2^+ + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\} \rightarrow T + T^+ + \left\{ \begin{array}{c} H^+ \\ D^+ \\ T^+ \\ He^{++} \end{array} \right\}$ Dissociation	(See Table 2.)

Table 1. (Continued.)

Reaction No.	Reaction	Reference
7	$T_2^+ + e^- \rightarrow T + T^+ + e^-$ Dissociation	D. F. Dance, H. F. A. Harrison, R. D. Rundell, and A. C. H. Smith, <i>J. Phys. B.</i> <u>92</u> , 577 (1967)
8	$T_2^+ + e^- \rightarrow 2T^+ + 2e^-$ Dissociation & Ionization	(See Table 7.)
9	$T + \begin{Bmatrix} H^+ \\ D^+ \\ T^+ \end{Bmatrix} \rightarrow T^+ + \begin{Bmatrix} H \\ D \\ T \end{Bmatrix}$ Hot Charge Exchange	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> , 363 (1971).
10	$T_2 + \begin{Bmatrix} H^+ \\ D^+ \\ T^+ \end{Bmatrix} \rightarrow T_2^+ + \begin{Bmatrix} H \\ D \\ T \end{Bmatrix}$ Hot Charge Exchange	C. F. Barnett, et al., <i>Atomic and Molecular Collision Cross Section of Interest in CTR</i> , Oak Ridge National Laboratory, ORNL-3113 Rev, Aug. 1964.
11	$T_2^+ + \begin{Bmatrix} H \\ D \\ T \end{Bmatrix} \rightarrow T_2 + \begin{Bmatrix} H^+ \\ D^+ \\ T^+ \end{Bmatrix}$ Charge Exchange	W. L. Fite, R. T. Brackmann, and W. R. Snow, "Charge Exchange in Proton-Hydrogen Atom Collision," General Atomic, GA-407, June, 1958.
12	$T_2 + \begin{Bmatrix} H_2^+ \\ D_2^+ \\ T_2^+ \end{Bmatrix} \rightarrow T_2 + \begin{Bmatrix} H^+ \\ D^+ \\ T^+ \end{Bmatrix} + \begin{Bmatrix} H \\ D \\ T \end{Bmatrix}$ Dissociation	K. K. Damodaran, <i>Proc. R. Soc. A.</i> , <u>239</u> 382 (1957).
13	$T + He^{++} \rightarrow T^+ + He^+$ Charge Exchange	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> , 363 (1971).
14	$T_2 + He^{++} \rightarrow T_2^+ + He^+$ Charge Exchange	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> , 363 (1971).

Table 1. (Continued.)

Reaction No.	Reaction	Reference
15	$T + He^{++} \rightarrow T^+ + He^{++} + e^-$ Ionization	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> , 363 (1971).
16	$T_2 + He^{++} \rightarrow T_2^+ + He^{++} + e^-$ Ionization	A. C. Riviere, <i>Nucl. Fusion</i> <u>11</u> , 363 (1971).

Table 2. General information. Included are the maximums of σ and σ/E , the range of experimental data which has been fitted, and general comments and reservations on the accuracy of SIGHDT.

Reaction	Max σ , 10^{-16} cm^2	$E \sigma (\text{Max})$, eV	Max σ/E , $10^{-8} \text{ cm}^2/\text{sec}$	$E \cdot V (\text{Max})$, eV	Range of Data	Comments
1) $T + p^+ \rightarrow T^+ + p^+ + e^-$ Ionization	1.8	7×10^4	6.5	1×10^5	7 keV to 170 keV	This is a fairly well known reaction and should be quite accurate. It should only be believed for energies $> 1 \text{ keV}$.
2) $T + e^- \rightarrow T + 2e^-$ Ionization	0.427	10^2	6.4	2×10^5	$E < 20 \text{ keV}$	We use Gryzinski's formulation for σ .
3) $T_2 + p^+ \rightarrow T^+ + p^+ + e^-$ Ionization	2.0	10^5	8.5	1×10^5	4 to 65 keV	The theoretical peak is at 150 keV, as we fit from 65-536 keV using value at 65 peak at 150. $\sigma=0$ for $E > 536 \text{ keV}$.
4) $T_2 + e^- \rightarrow T_2^+ + 2e^-$ Ionization	0.99	60	6.1	120	15 eV to 20 keV	This is also fairly well known and is expected to be quite accurate.
5) $T_2 + e^- \rightarrow 2T + e^-$ Dissociation	0.9	20	2.2	20	10 to 80 eV	This reaction is of little interest for energies much greater than 100 eV.
6) $T_2^+ + p^+ \rightarrow T + T^+ + p^+$ Dissociation	12.6	10^4	25	10^5	None	No data is available on this reaction. We used a peak σ of twice the electron dissociation reaction and placed it at an energy such that $v \approx v$ electron at threshold for the electron reaction. At high energies, this cross section goes to the electron cross section.
7) $T_2^+ + e^- \rightarrow T + T^+ + e^-$ Dissociation	4.15	10	8.2	140	5 eV to 1 keV	$\sigma = 0$, $E > 7035 \text{ keV}$

Table 2. (Continued)

Reaction	Max σ , 10^{-16} cm ²	$E_{\sigma}(\text{Max})$, eV	Max σV , 10^{-8} cm ³ /sec	$E_{\sigma V}(\text{Max})$, eV	Range of Data	Comments
8) $T_2^+ + e^- \rightarrow T_2^+ + 2e^-$ Dissociation Ionization	2.1	25	5.9	25	None	No data is available on this R_x . We used a peak of half of No. 7 and a threshold energy of 20 eV.
9) $T + P_{\text{Hot}}^+ \rightarrow T^+ + P_{\text{Hot}}$	68	1	14	10^4	.4 keV to 130 keV	The cross section is divergent at $E = 0$, but $\langle \sigma V \rangle$ is going to 0 as would be expected.
10) $T_2 P_{\text{Hot}}^+ \rightarrow T_2^+ + P_{\text{Hot}}$ Charge Exchange	10.5	5×10^3	13.5	1×10^6	10 keV to 10 eV	This is a fairly well known cross section.
11) $T_2^+ + P \rightarrow T_2 + P^+$ Charge Exchange	11	9×10^2	5.6	2×10^3	1 keV to 10 keV	The data on this reaction is extremely sparse; most of the generated cross section is extrapolation.
12) $T_2 + P_2^+ \rightarrow T_2 + P + P$ Dissociation	2.8	2×10^5	15.8	4×10^5	200 keV to 10 eV	The data on this is also sparse; the low energy range has been totally extrapolated.
13) $T + He^{++} \rightarrow T^+ + He^+$ Charge Exchange	16.6	3×10^4	23	7×10^4	0.1 keV to 300 keV	The data is fairly well represented by Riviere.
14) $T_2 + He^{++} \rightarrow T_2^+ + He^+$ Charge Exchange	33	3×10^4	46	4×10^4	0.1 keV to 300 keV	Twice the atomic cross section is used for the molecular reaction.
15) $T + He^{++} \rightarrow T^+ + He^{++} + e^-$ Ionization	7.2	2×10^5	26	4×10^5	None	In this and number 16, Riviere's fits for protons (Reaction number 1) is used after being properly modified for mass and charge effects.
16) $T_2 + He^{++} \rightarrow T_2 + He^{++} + e^-$ Ionization	14.5	2×10^5	52	4×10^5	None	See No. 15 above.

APPENDIX

Source Listing of SIGHDT

FUNCTION SIGHDT(NREACT,EN)
OPTIMIZE

```

C      THIS ROUTINE CALCULATES CROSS SECTIONS FOR THE FOLLOW-
C      ING REACTIONS.
C      ***** REACTION LIST *****
C      1      D1D+,E-1D+
C      2      D1T+,E-1D+,T+
C      3      D1ALPHA++,E-1D+,ALPHA++
C      4      D2(E-,2E-1D2+
C      5      D2(E-,E-1D2+
C      6      D2(DHOT+,DHOT)D2+
C      7      D1(DHOT+,DHOT)D+
C      8      D1(THOT+,THOT)D+
C      9      T1(DHOT+,DHOT)T+
C      10     T1(THOT+,THOT)T+
C      11     D2+1D,D-1D2
C      12     D2+1D2,U2,E-1D2+
C      13     D2+1D+,2D+1D
C      14     D2+1E-,E-1D,D+
C      15     D2+1E-,2E-1D2+
C      16     D1E-,2E-1D+
C      17     D2(D+,D+,E-1D2+
C      *****
C      THE ENTRY POINTS TELL THE FUNCTION WHETHER TO CALCULA-
C      TE SIGHOT OR SIGHDT? V.
C      TE SIGHDT(SIG-) OR SIGHOT(VISIGV-). THEY ALSO PASS THE
C      CORRECT MASS TO THE VELOCITY CALCULATION. TO ADD MORE
C      REACTIONS TO THE LIST INCLUDE THE LOCATION OF THE
C      STARTING LABEL(LN) IN THE DATA STATEMENT FOR ADDR.
C      EXAMPLE: DATA(ADDR=.LOC.L1,....,LOCLK,....,LOCLN)
C      ADDR=SS ADDR(100)
C      DATA(ADDR=.LOC.L1,.LOC.L2,.LOC.L3,.LOC.L4,.LOC.L5,.LOC.L6,.LOC.L7,
C      .LOC.L7,.LOC.L9,.LOC.L10,.LOC.L11,.LOC.L12,.LOC.L13,.LOC.L13,
C      .LOC.L15,.LOC.L15)
C      REAL LOGSIGHDT,LNE,M1,M2,LNE2,LNEDE
C      DATA(CEV=1.39E6),(HMASS=1.),(DMASS=2.),(DMASS=4.)
C
C      VELOCITY CALCULATION FUNCTION
C
C      VEL(A)=A*SQRT(1/(EN/M1))
C      VELR(A)=3.E10*SQRT(1/(1.-A*A))
C      PARAMETER(AO=8.84E-17)
C      ENTRY SIGH(NREACT,EN)
C      M1=1.      $ ZSQUARE=1.
C      JSV=0
C      GO TO SELECT
C      ENTRY SIGD(NREACT,EN)
C      ZSQUARE=1.
C      M1=2.
C      JSV=0
C      GO TO SELECT
C      ENTRY SIGT(NREACT,EN)
C      ZSQUARE=1.
C      M1=3.
C      JSV=0
C      GO TO SELECT
C      ENTRY SIGE(NREACT,EN)
C      ZSQUARE=1.
C      M1=5.486E-4

```

```

JSV=0
GO TO SELECT
ENTRY SIGD2(NREACT,EN)
ZSQUARE=4.
M1=4.
JSV=0
GO TO SELECT
ENTRY SIGE1(NREACT,EN)
ZSQUARE=4.
M1=4.
JSV=0
GO TO SELECT
ENTRY SIGD2(NREACT,EN)
ZSQUARE=4.
M1=4.
JSV=1
GO TO SELECT
ENTRY SIGH2(NREACT,EN)
M1=2. $ ZSQUARE=4.
JSV=0
GO TO SELECT
ENTRY SIGVH(NREACT,EN)
M1=1. $ ZSQUARE=1.
JSV=1
GO TO SELECT
ENTRY SIGVH2(NREACT,EN)
M1=2. $ ZSQUARE=4
JSV=1
GO TO SELECT
ENTRY SIGVH2(NREACT,EN)
ZSQUARE=4.
M1=4.
JSV=1
GO TO SELECT
ENTRY SIGVD(NREACT,EN)
ZSQUARE=1.
M1=2.
JSV=1
GO TO SELECT
ENTRY SIGVT(NREACT,EN)
ZSQUARE=1.
M1=3.
JSV=1
GO TO SELECT
ENTRY SIGVE(NREACT,EN)
ZSQUARE=1.
M1=5.486E-4
JSV=1
SELECT E0=9.3148E8*M1 $ CHECK=EN-.01*E0 $ GO TO ADDR(NREACT)
C
C REACTION 1 D:D+U)2D+
L1 ENERGY=HMASS/M1*EN $ LNE=LOG1(ENERGY)
IF(ENERGY.LT. 13.61Y1,A1
A1 IF(ENERGY.LT. 150000.),B1
LOGSIGHDT=-.3784*LNE*LNE+B.156*LNE-80.206
SIGHDT=EXP1(LOGSIGHDT)*ZSQUARE
GO TO X2
B1 LNE=LOG1(.1666*ENERGY)
SIGHDT=(1.563E-12*LNE/ENERGY)*ZSQUARE
GO TO X2

```

```

C
C
C      REACTION 2  D2(E-,2E-)D+
C
L2 ENERGY=EN $ IF(ENERGY .LT. 13.6)Y1,A2
A2 E=ENERGY/13.6 $ LNE=LOG1(E)
SIGHDT=(1.19*(E+2.56)-(E-1.)/(E+E+1.67*E+3.57)*A0
GO TO X2
C
C
C      REACTION 3  D2(D+,D+,E)D2+
C
L3 ENERGY=OMAC*(M1*EN+1.E-3 $ LNE=LOG1(ENERGY)
IF(ENERGY .LT. .015461)Y1,A3
A3 IF(ENERGY .LT. 65.1),B3
LOGSIGHDT=-40.93+1.41*LNE-.092*LNE*LNE
SIGHDT=EXP1(LOGSIGHDT) $ GO TO X2
B3 IF(ENERGY .GT. 536.)Y1,
SIGHDT=-2.641E-15+1.133E-15*LNE-1.129E-16*LNE*LNE $ GO TO X2
C
C
C      REACTION 4  D2(E-,2E-)D2+
C
L4 ENERGY=EN $ LNE=LOG1(ENERGY)
IF(ENERGY .LT. 15.461)Y1,A4
A4 IF(ENERGY .LT. 20.) ,B4
SIGHDT=(1.329*LNE-3.638)*A0
GO TO X2
B4 IF(ENERGY .LT. 26.) ,C4
SIGHDT=(1.1548-1.051*LNE+.3717*LNE*LNE)*A0
GO TO X2
C4 IF(ENERGY .LT. 32.) ,D4
SIGHDT=(-2.2+.9496*LNE+.0089*LNE*LNE)*A0
GO TO X2
D4 IF(ENERGY .LT. 44.) ,E4
SIGHDT=(-12.451+6.807*LNE-.857*LNE*LNE)*A0
GO TO X2
E4 IF(ENERGY .LT. 57.) ,F4
SIGHDT=(1.3727+.1655*LNE+.004*LNE*LNE)*A0
GO TO X2
F4 IF(ENERGY .LT. 71.) ,G4
SIGHDT=(-12.257+6.414*LNE-.7689*LNE*LNE)*A0
GO TO X2
G4 IF(ENERGY .LT. 110.) ,H4
SIGHDT=(-5.02+2.88*LNE-.338*LNE*LNE)*A0
GO TO X2
H4 IF(ENERGY .LT. 250.) ,I4
EL=LNE/ENERGY
SIGHDT=(.064+37.108*EL-329.15*EL*EL)*A0
GO TO X2
I4 IF(ENERGY .GT. 15210.5)Y1,
AM10=1.8778E-8-1.95E-9*LNE
SIGHDT=AM10*AM10
GO TO X2
C
C
C      REACTION 5  D2(E-,E-)D2
C
L5 ENERGY=EN $ LNE=LOG1(ENERGY) $ ENL2=LNE*LNE
IF(ENERGY .LT. 8.)Y1,A5
A5 IF(ENERGY .LT. 12.1),B5
LOGSIGHDT=-1561.995+1887.79*LNE-770.89*ENL2+105.1*ENL2*LNE
GO TO X1

```

```

B5 IF (ENERGY .LT. 17.5) ,C5
LOGSIGHDT=-46.08+19.64*LNE-3.39*ENL2
GO TO X1
C5 IF (ENERGY .LT. 52.) ,D5
LOGSIGHDT=-27.16+6.57*LNE-1.14*ENL2
GO TO X1
D5 LOGSIGHDT=-48.06+16.68*LNE-2.36*ENL2
GO TO X1

C
C REACTION 6 D2+(D+,2D+)D
L6 ENERGY=EN $ LNE=LOGI(ENERGY) $ LNE2=LNE*LNE
IF (ENERGY .LT. 4.)Y1,A6
A6 IF (ENERGY .LT. 14686.) ,B6
SIGHDT=(-5.0021+3.8893*LNE-.2037*LNE2)*A0
GO TO X2
B6 IF (ENERGY .LT. 25000.) ,C6
SIGHDT=(-200.625+44.9861*LNE-2.361*LNE2)*A0
GO TO X2
C6 IF (ENERGY .LT. 9.E5) ,D6
SIGHDT=(43.66477-3.0561*LNE)*A0
GO TO X2
D6 IF (ENERGY .LT. 2.7E6) ,E6
SIGHDT=(161.343-21.356*LNE+0.7092*LNE2)*A0
GO TO X2
E6 ENERGY=3.4E-4*ENERGY $ LNE=LOGI(ENERGY)
LNEDE=LNE/ENERGY $ GO TO D7

C
C REACTION 7 D2+(E-,E-)D,D+
C REACTION 8 D2+(E-,2E-)2D+
C

L7 ENERGY=EN
IF (NREACT .EQ. 8) ENERGY=ENERGY-16.
IF (ENERGY .LT. 4.)Y1,A7
A7 LNE=LOGI(ENERGY) $ LNEDE=LNE/ENERGY
IF (ENERGY .LT. 5.) ,B7
SIGHDT=(-38.8087+27.9945*LNE)*A0
GO TO E7
B7 IF (ENERGY .LT. 8.5) ,C7
SIGHDT=(-26.395+35.238*LNE-9.293*LNE*LNE)*A0
GO TO E7
C7 IF (ENERGY .LT. 75.) ,D7
SIGHDT=(-9359+30.596*LNEDE-34.44*LNEDE*LNEDE)*A0
GO TO E7
D7 IF (ENERGY .LT. 1000.) ,D7A
SIGHDT=(-1615+63.681*LNEDE-375.631*LNEDE*LNEDE)*A0
GO TO E7
D7A SIGHDT=5.68076E-15*EXP1(-.685457*LNE)
E7 IF (NREACT .NE. 6) SIGHDT=.666666667*SIGHDT
IF (NREACT .EQ. 8) SIGHDT=SIGHDT*.5
GO TO X2

C
C REACTION 9 D(DHGD+,DHOD)D+
C

L9 ENERGY=HMASS/M1*EN $ LNE=LOGI(ENERGY)
AMID=1.-.06732*LNE
SIGHDT=(6.937E-15*AMID*AMID)/(1.+1.112E-15*ENERGY**3.3)
GO TO X2

C
C REACTION 10 D2(DHOT+,DHOT)D2+

```

```

L10 ENERGY=DMASS/M1*EN      $ LNE=LOG1(ENERGY)
    IF (ENERGY .LT. 9050.) ,A10
    LOGSIGHDT=-42.51+5.31*LNE-.266*LNE*LNE
    GO TO B10
A10 LOGSIGHDT=-55.23+7.79*LNE-.385*LNE*LNE
B10 SIGHDT=EXP1(LOGSIGHDT)    $ GO TO X3
C
C    REACTION 11 D2+(D,D)+D2
L11 ENERGY=D2MASS/M1*EN+1.E-3      $ LNE=LOG1(ENERGY)
    IF (ENERGY .LT. 3.) ,A11
    LOGSIGHDT=-34.58+.24*LNE-.109*LNE*LNE
    GO TO B11
A11 LOGSIGHDT=-34.71+.478*LNE-.219*LNE*LNE
B11 SIGHDT=EXP1(LOGSIGHDT)    $ GO TO X2
C
C    REACTION 12 D2+(D2,D2)+D2
L12 ENERGY=EN+1.E-3          $ LNE=LOG1(ENERGY)
    LOGSIGHDT=-48.21+4.52*LNE-.412*LNE*LNE
    SIGHDT=EXP1(LOGSIGHDT)
    GO TO X2
C
C    REACTIONS 13 AND 14 ALPHA PARTICLES
L13 ENERGY=EN      $ LNE=LOG1(ENERGY)
    IF (ENERGY .LT. 12000.) ,A12
    LOGSIGHDT=-38.08+.039*LNE*LNE
    SIGHDT=EXP1(LOGSIGHDT)
    IF (NREACT .EQ. 14) SIGHDT=SIGHDT*2.          $ GO TO X2
A12 LOGSIGHDT=-34.03+.5776*(10.36-LNE)**2
    SIGHDT=EXP1(LOGSIGHDT)
    IF (NREACT .EQ. 14) SIGHDT=SIGHDT*2.          $ GO TO X2
C
C    REACTIONS 15 AND 16 ALPHA PARTICLES
L15 ENERGY=HMASS/M1*EN
    LNE=LOG1(ENERGY)
    IF (NREACT .EQ. 16) ZSQUARE=2.*ZSQUARE
    IF (ENERGY -13.6)Y1,Y1,A1
C
C    SEND BACK SIGMA OR SIGMA-V
C
C
X1 SIGHDT=EXP1(LOGSIGHDT)    $ GO TO X3
X2 IF (JSV .NE. 0) ,Z3
    IF (CHECK) ,Z1,Z1
    SIGHDT=SIGHDT*VEL(CEV)    $ RETURN
X3 IF (JSV .EQ. 0) ,Z3
    IF (CHECK) ,Z2,Z2
    SIGHDT=SIGHDT/VEL(CEV)    $ RETURN
Y1 SIGHDT=0.      $ RETURN
Z1 SIGHDT=SIGHDT*VELR(E0/(E0+EN))    $ RETURN
Z2 SIGHDT=SIGHDT/VELR(E0/(E0+EN))    $ RETURN
Z3 RETURN
END

```